AD NUMBER

AD135780

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

No foreign

AUTHORITY

NRL ltr. 7103/911, 25 Aug 1999

NAVAL RESEARCH LABORATORY REPORT

December 3, 1940

THE EFFECT OF WATER CONDITIONS ON THE PROPAGATION OF SUPERSONIC UNDERWATER SOUND

By
E. B. Stephenson

Report No. S-1670

Classification changed from CONFIDENTIAL
To UNCLASSIFIED
By authority of Navy Regulation
File No. Art. 76, pp. 56 Dated 1920

NAVY DEPARTMENT
OFFICE OF NAVAL RESEARCH
NAVAL RESEARCH LABORATORY
WASHINGTON 20, D. C.

3 December 1940 NRL Report No. S-1670

NAVY DEPARTMENT

Report on
The Effect of Water Conditions on the Propagation
of Supersonic Underwater Sound

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D. C.

Number of Pages: Text - 14 Plates - 13

Authorization: Problem U5-2C, BuShips ltr. C-NC/S68 (4-15-R4-6/24) of 4-27-39.

Date of Tests: Summary - 1931-1940.

Reported by: E. B. Stephenson, Senior Physicist

Reviewed by: H. C. Hayes, Principal Physicist, Superintendent Sound Division

Approved by: H. G. Bowen, Rear Admiral, U.S.N., Director

Distribution: C.N.O (Fleet Training)-(40)
BuShips-(10)
1 Copy Capt. V. D. Herbster, N.Y. Boston 1-14-41

EBS:np

ABSTRACT

The purpose of this report is to consolidate well established theory and the data available to date and make such generalizations as the facts warrant. The factors in water conditions affecting sound propagation are discussed in detail, and the applications of the principles are illustrated by examples and experimental data.

It is concluded that water conditions frequently set definite limitations on the use of underwater sound gear, but also that a proper knowledge and understanding of the conditions frequently permits taking tactical advantage of the limitations. Great care must be used not to make too broad generalizations from limited data, as conditions may vary greatly and rapidly with time or place.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

PLATES

THE EFFECT OF WATER CONDITIONS ON THE PROPAGATION OF SUPERSONIC UNDERWATER SOUND

1. Introduction

During the past ten years a large amount of data on the performance of supersonic sound equipment has been accumulated. The results obtained have varied widely for reasons that were not always obvious because all the necessary facts were not known or understood. There are three important factors upon which the results depend. These are:

(a) The equipment,

(b) The operating personnel and technique,

(c) The water conditions.

This article will be limited to a discussion of the effect of water conditions on sound propagation.

From a knowledge of the physics of wave motion in a fluid medium, the behavior of a sound beam in water could be predicted if all the necessary constants were known, but the water conditions are often complex and all the factors are seldom known with accuracy, so that only general statements may be made in many cases. As accurate experimental data are accumulated on sound propagation under different conditions, times, and places, these generalizations may be made more specific and accurate. The purpose of this report is to consolidate the data now available on the effect of known water conditions on sound propagation in sea water and to make such generalizations as seem warranted. The theory and data on which the generalizations are based may be found in standard text books on sound and the reports listed in the bibliography.

2. Sound as Wave Motion

Underwater sound is propagated as a longitudinal vibration; that is, an alternate compression and rarefaction in the medium as contrasted with the transverse vibration of electromagnetic or light waves, but the two types of waves follow the same general laws. Thus, the sound waves have a definite velocity under a definite condition and are subject to reflection, refraction, diffraction, scattering and absorption. The velocity is determined by the elasticity and density of the medium and these in turn vary with temperature, pressure, and salinity of the sea water. Any abrupt change in the velocity causes at

least part of the energy to be reflected, and a gradual change causes refraction or bending of the path. Scattering is caused by reflecting areas that are small or irregular compared with the wave length, and absorption occurs when the sound energy is transformed into heat.

3. Factors in Water Conditions Affecting Sound Propagation

The principal factors in water conditions that affect sound propagation are: the temperature and the temperature gradient, the salinity and the salinity gradient, the pressure and the pressure gradient, the turbulence or cavitation, and the marine growths. These in turn are affected by variable cycles in the sea, sky, wind, rainfall, weather and current conditions. These factors are not all independent and their importance and correlations vary with time and place, but there are numerous general rules that may be based on present theory and experience.

4. Temperature and Temperature Gradients

The velocity of sound in sea water of 35 parts per thousand salinity varies with the temperature as shown on Curve 1 of Plate 1. The units are meters and centigrade degrees (1 meter = 1.0936 yards and $^{\circ}F = 1.8^{\circ}C + 32$.) The data from which the curve is plotted are the best available and values read from the curve are accurate within 0.2 meters per second. The rate of change of the velocity with temperature is the temperature coefficient of velocity, and it varies with the temperature as shown on Curve 2 of Plate 1. Thus from Curve 1, one finds the velocity at 20°C to be 1518.7 m/sec. and from Curve 2 that at 20°C the velocity changes at the rate of 2.78 m/sec. per °C or 0.175% per °C. The magnitude of this effect is large enough to be important as will be shown later.

When a sound beam is transmitted through a medium in which the temperature and therefore the velocity of sound, changes either vertically or horizontally with distance, the beam will be refracted. The path of the axis of a refracted beam is approximately along the circumference of a circle whose center and radius are determined by the temperature, the temperature gradient, and the initial angle of the beam with respect to the direction of the gradient. Gradients are normally measured in a vertical direction as the rate of change of the temperature with depth, or in a horizontal direction as the rate of change of the temperature with range. When the temperature increases as the depth increases, the gradient is defined as positive and tends to refract the sound beam upwards. When the temperature decreases as the depth increases (the most common condition) the gradient is called negative and tends to bend the sound beam downward. A warm

layer of water between two colder layers is called an inversion and is indicated by changes in sign of the gradient. A sound beam above the inversion is bent upward and a beam below it is bent downward so that the inversion layer tends to act as a barrier for sound transmission. When the path of the beam coincides with the direction of the gradient there is a change in velocity of the sound but no bending of the beam.

5. Salinity and Salinity Gradients

The salinity affects the velocity of sound in water as shown by Curve 3 of Plate 1. The velocity increases as the salinity increases, but the rate of change of velocity depends on the temperature. The salinity of sea water may range from 30 to 37 parts per thousand (ppt) with 35 ppt as a fair average value. Curve 1 is for 35 ppt salinity. Curve 3 is used to calculate the velocity at any other salinity The values of the salinity and the rate of change with depth in the open sea vary with the geographical location and with the current, rainfall, and evaporation conditions.

The same convention will be followed in designating salinity gradients as was used for temperature gradients. A positive gradient is one in which the salinity, and therefore the velocity, increases with depth and tends to refract the beam upwards. A negative gradient is one in which the salinity decreases with depth and tends to refract the beam downward.

Fairly well defined and often abrupt changes in both the horizontal and vertical salinity gradients may be found, especially near the mouths of large rivers or bays. The data on salinities are not as complete as on temperatures, largely due to the technical difficulties of measurements, but fortunately the salinity effect on sound propagation is relatively small compared to the temperature effect.

6. Depth

The velocity of sound increases with the depth at a practically constant rate of 0.0181 meters per second per meter increase in depth down to a depth of 400 meters. The pressure gradient is always positive and tends to bend the sound beam upward. A correction for the change in the velocity of sound with depth is made when echo-sounding for hydrographic surveys, but it is seldom necessary in routine navigational use of sounding gear.

7. Turbulence and Cavitation

Turbulence and cavitation in the path of a sound beam scatter the sound energy much as clouds or a smoke screen scatter the light from the sun. This results in a loss of intensity on the axis of the beam of

the transmitted ray, but some of the energy will be scattered back towards the source and an echo is often heard. Such an echo is usually weak, diffuse and drawn out more than a true target echo. The amount of the scattering depends on the size of the turbulent vortices compared to the wave length of the sound used. The lower frequencies penetrate turbulence better than the higher frequencies and correspondingly high frequencies give better echoes from turbulence. There is always turbulence near the boundary when one body of water moves with respect to another or when the water is mechanically disturbed. Thus echoes may often be obtained from the bottom of the Gulf Stream, off the wake of a ship or off a school of fish.

8. Marine Growth

It is frequently found that poor sound propagation is found to coincide with evidence of microscopic marine growth. It has not been determined that the marine growth, either animal or vegetable, is itself the cause of the poor propagation of a sound. It seems more probable that the marine growth is evidence of certain temperature and salinity conditions, and these in turn are usually such as to cause poor propagation of sound. Thus echo-ranging has been found to be poor in the "red water" condition in Panama Bay, but it may also be poor in nearby areas where there is no "red water."

9. Sea Surface

The sea surface affects the propagation of sound in several ways. If the vertical distances between the troughs and crests of the waves are greater than the average depth of submergence of the projector, part of the time the axis of a horizontal beam and everything above it will be cut off by the trough of the wave. If the ship is pitching with the projector on a 0° bearing, or rolling with the projector on a 90° bearing, the axis of the beam sweeps through the whole angle of roll. The magnitude of this effect can be seen from Plate 3. Thus, for a 10° downward roll on a 90° bearing, the axis is in the position of the -10° ray, is down 530 feet at 1000 yards and the intensity of the horizontal ray would be down 10.8 db. from the axial intensity. On the corresponding upward roll, the -10° ray of Plate 3 would be horizontal, everything above it would be scattered by the waves and the intensity would be down 10.8 db. The direct signal, therefore, would vary by ± 10.8 db. during the roll and the echo might well vary twice this amount. Practically, this means that echo-ranging on a bearing where the pitch or roll causes this effect should be avoided if possible.

A dead calm sea is frequently unfavorable for echo-ranging for two reasons. The air-water surface reflects the sound like a mirror, but with 180° change in phase. Plate 3 shows that any ray within 3°

of the axis is down only 1 db. or less. Since the paths and intensities of the axis ray and the rays within 3° above it are so nearly equal, the 180° phase difference causes interference or partial cancellation and a considerable loss of axial intensity. Also, the conditions causing a calm sea are frequently favorable for building up steep temperature gradients, or a series of small inversions that cause irregular refractions of the beam.

10. Sky Conditions

Under sky conditions are included the intensity of the sunlight and the clouds, fog or haze which to a certain extent modify the intensity at the sea surface. The light from the sun which strikes the surface of the sea is partly reflected and is partly transmitted into the water where it is finally converted into heat. About one third of the total energy from the sun is in the infra-red region. This energy is all absorbed in the first few inches of water. The energy of the visible light, even in the clearest known sea water, is absorbed so rapidly that 90% of it has been transformed into heat in the first 125 feet. This results in a relatively intense heating of a shallow upper layer and the development of steep temperature gradients. At night the process is generally reversed. The surface water being warmer than the air loses heat by radiation and by evaporation. Radiation is greatest on a calm, clear night but evaporation depends primarily on the air and water temperatures, the relative humidity and the wind. In hot calm weather in the Caribbean, one frequently finds a series of alternately warm and cool layers, corresponding to alternate heating and cooling effects of day and night, extending down to a depth of 100 feet or more. The layers are generally thicker and the temperature differences less as the depth increases.

11. Wind

The importance of the stirring action of the wind on temperature gradients has only recently been understood. The facts had been well established by work on the Semmes and the explanation was given by Dr. Langmuir of the General Electric Company in 1938. To summarize briefly, he shows that the effect of the wind is to produce a series of right and left helical vortices in the water having horizontal axes parallel to the direction of the wind. The water descends under the wind streaks and rises between the streaks. While this motion is slow it gives rise to a generally turbulent condition that thoroughly mixes the water. A windy day causes the temperature gradient to disappear down to a certain depth but produces a very sharp gradient at the lower limit of the isothermal layer. The velocity of the wind and the time during which the velocity is maintained roughly determine the depth of the stirring action.

The surface indication of this is the spacing between the wind streaks or the distance between the "windrows" of seaweed or kelp, the spacing being determined by the sustained wind velocity, and the depth of the stirring action being approximately proportional to the distance between streaks. There is positive experimental evidence that the stirring action of a 20 knot wind for 6 hours may extend down more than 125 feet in deep water where the wind has a long sweep as off Guantanamo, but off Panama Bay even in deep water the stirring action is limited to about 50 feet probably because the northeast wind does not have time to build up the stirring action.

12. Weather

A knowledge of the weather conditions for two or three days preceding a sound test is a help in estimating the results that may be expected from the sound equipment. The estimate is a practical application of the principles stated above and may be illustrated by an example: On a clear, fairly calm day after a northwest storm in open water off the New England coast but within the 100 fathom curve, the listening and echo-ranging conditions are excellent and will probably continue excellent for several days in the winter time. In the summer time by the afternoon of the second day after the storm, echo-ranges will usually be short and false contacts often will be made, but propeller noise ranges may be good. Occasionally "skip distance" echo effects will be found. The explanation is that the storm thoroughly mixes the water and the temperature gradients are small or zero down to about 150 feet. This condition lasts for several days during the winter because the intensity of the sunlight is low and the water warms up slowly. In the summer the heating effect is greater and gradients build up more rapidly. This bends the beam downward and since the water is shallow, echoes will be obtained from the bottom giving false contacts or ranges. The propeller noise is reflected from the bottom without much loss of intensity so listening may be rated as good.

13. Measurements and Estimates of Water Conditions

The only certain and accurate means of determining how the water conditions affect sound propagation is an experimental sound test with the proper target and equipment at the particular time and place. Even such an experimental determination gives no assurance that the data will be valid for more than a limited change in time or place. However, since the tactical situation may not permit an experimental test, it is proposed to discuss supplementary data and methods of obtaining them that will aid in making a valid estimate of the situation. Obviously, all possible cases cannot be covered, but enough will be given to illustrate the technique and type of reasoning so that anyone familiar with points covered in the preceding paragraphs should be able to apply the available information to the particular situation and to make an estimate of the results to be expected from the sound gear.

A submarine may detect large temperature changes as she makes a slow dive by reading the injection water temperature or by taking samples in a bucket. This is a slow and crude method, and there probably is a big time lag. Better results may be obtained by mounting a thermometer outside an eyeport in the conning tower. By going down in 10 foot stages and allowing 2 minutes at each stage, readings may be taken to ± 0.1°C with a good thermometer. Several thermometers are necessary to cover with sufficient accuracy the full range of temperatures met with in the Atlantic Ocean in a seasonal cycle. The Naval Research Laboratory has developed a direct reading temperature gradient indicator for submarines. Preliminary experiments indicate that gradients as small as 0.01°C per fathom or as large as 5°C per fathom may be read directly from a meter scale. The indicator is particularly sensitive to temperature inversions as a change in sign of the gradient causes a quick swing of the needle from one side to the other. The equipment is small and no adjustments are necessary during the dive.

For destroyers, the Bureau of Ships has developed a bathythermograph which may be lowered over the side at a rate of about 1 foot per second to a depth of 500 feet. It automatically traces a pressure-temperature curve on a small smoked glass slide. When the slide is placed in a projection lantern the curve is projected onto an 8" x 10-1/2" calibrated chart from which the temperatures can be read to ± 0.1°F and the depths to ± 1 ft. Since one coordinate is pressure, the length or angle of the wire need not be measured, but it is necessary for the ship to lie to or to run at very slow speed for about 20 minutes to make a temperature-depth measurement to 500 feet.

An investigation of the possibility of making salinity measurements has been made but at present there is no known method that is considered practical for general naval service use. Salinity measurements can be made with accuracy on a ship properly equipped for hydrographic or oceanographic work, but at present the information obtainable is probably not worth the cost in space, equipment and personnel on a combatant Navy ship. Fortunately, the salinity effect on sound propagation is in general relatively small compared to the temperature effect except under some special condition, as where fresh and salt water are mixing.

14. The Path of a Sound Beam

It is possible to calculate the path of a sound beam under certain specified conditions. The mathematical formula is somewhat complex and the calculations laborious so only a few typical examples will be given to illustrate the general principles. The derivation of the mathematical formula and the details of the calculations will be given in a separate technical report.

On Plate 2 are shown the paths of the axis of an initially horizontal sound beam subject to the refracting effect of the pressure gradient and of the temperature gradients as marked. The projector is located 500 feet below the surface and the water is assumed to be homogeneous except for the pressure and the temperature gradients shown. This depth is obviously a hypothetical case given to demonstrate the principle. Decreasing the depth of submergence would not change the lower half of the picture, but the rays in the upper half would suffer reflection at the air-water surface. The vertical scale is 15 times the horizontal scale so the bending effect is exaggerated. It is interesting to note that under a condition of zero temperature gradient the beam is bent upward due to the pressure gradient and that it takes a negative temperature gradient of approximately .006°C/m to give a horizontal beam. For a negative gradient of .03° C/m, which is often found in the Atlantic Ocean, it will be seen that the axis is bent downward 50 feet at 900 yards, 100 feet at 1300 yards, 200 feet at 1700 yards and 570 feet at 3000 yards.

A sound beam always has a certain spread. Plate 3 shows the depth to which a ray making a given angle with the axis will penetrate at any range. The decibel figures show how much the intensity at the specified angle off the axis will be below the axial intensity. The intensity figures are for a 19 inch, 24 kilocycle projector and the medium is assumed to be homogeneous.

On Plate 4 are shown a set of curves for a projector on a destroyer with the axis of the beam initially 13 feet below the surface. The temperature gradient is -0.1° F/fm = -0.03° C/m, the salinity is uniform at 35 parts per thousand (ppt) and the initial temperature is 20° C at 13 feet. The curvature of the axis of the beam is the same as the -0.03° C/m curve of Plate 2. The ray +1° 6' above the axis just grazes the surface - assumed to be smooth - and a ray at any angle greater than this will be reflected and cross to the lower side of the axis as shown by the +5° ray. Since there is usually some roughness at the sea surface, any ray above the axis will probably be scattered or reflected, and, therefore, the axis becomes practically the upper and limiting edge of the beam. This edge is quite sharply defined and will pass under a surface vessel at about 1000 yards. This is checked by the common experience of a sudden and complete loss of the echo at relatively short ranges when there is a negative temperature gradient as specified. A submarine, trying to avoid detection, should stay as near the surface as possible when in water with a fairly large negative gradient.

For a destroyer installation, the curves also show the futility of attempting to tilt the projector upward to compensate for the downward bending of the beam. Even on a submarine, tilting the projector is unnecessary because of the beam spread and intensities as shown in Plate 3.

In Plate 5 is shown a temperature gradient with an inversion of a type and degree occasionally found in the Caribbean. Plate 6 shows the paths of the sound beam from a projector on a destroyer under the temperature conditions of Plate 5. The central cone of the beam within the limits ± 2° 49' is confined to the layer above the temperature inversion depth and all the rest of the beam outside the central cone is bent sharply downward and lies below the ±2° 50' curve. There is thus a "deaf" zone bounded by the level of the temperature inversion above and the ±2° 50' curve [illegible] the [illegible] the [illegible] deaf zone the destroyer can get no echoes from the submarine nor can it hear the submarine's propellers. Although the propeller noise radiates in all directions, any ray at less than the critical angle will not pass through the inversion and any ray at a greater than critical angle will pass through and be reflected downward from the air-water surface. The boundaries of the deaf zone are determined by the paths of the rays, and, since the beam pattern of a projector is independent of the sound power output, the boundaries of the deaf zone would not be affected by an increase in power output. The safest position for the submarine is the minimum depth at which she is completely below the temperature inversion layer.

In the layer above the temperature inversion depth, the echo ranges will be relatively long, possibly 5000 yards, but there will be rapid and frequently large variations in intensities in a short distance due to reinforcements and interferences by rays following different paths, or between refracted rays and rays reflected at the air-water surface with a 180° change in phase. (See Plate 9)

The refraction effects of Plate 6 are for the particular temperature gradients of Plate 5, but some qualitative generalizations are possible:

(a) The boundaries of the deaf zone are not materially affected by variations in the gradient of the layer above the inversion depth, but as the gradient goes from negative to positive values, more sound is concentrated in the upper layer and less sound penetrates the inversion.

(b) Changing the depth of the inversion layer merely raises or lowers the ceiling without changing the lateral boundary which is determined by the critical angle curve, but a shallow inversion layer would concentrate relatively more energy in the upper layer and conversely.

(c) Increasing the gradient in the inversion layer would increase the critical angle, reduce the range, increase the steepness of penetrating ray and thus increase the deaf zone on the side towards the destroyer.

(d) An increase of salinity in the inversion layer would produce the same effect as an increase in the gradient as given in (c) above. Since these temperature inversions often continue for several days, it seems necessary to assume an increase in salinity in the layer to maintain a uniform density gradient; otherwise, the lighter warm layer could not be in equilibrium with the colder layers above and below it.

Plate 7 shows the case for a submarine at 150 feet under the temperature gradient conditions of Plate 6. This shows a critical angle of 4° 31'. All rays striking the inversion layer at less than this angle will be refracted downwards, and only those on the upper side of the beam making an angle of 4° 31' or greater can strike a target near the surface. The deaf zone is therefore bounded by the surface and by the critical angle ray. The range is limited to 1000 yards or less by the angle and also by the lower intensity of the rays 5° or more off the axis of the beam. Theoretically, the submarine may increase the echo range a few hundred yards by going to greater depths, but the echo intensity would be low, as the ray striking the inversion layer at the critical angle would be 5° or more off the axis of the beam. If the submarine goes to a depth just under the temperature inversion layer she is less liable to be detected, but she also has a shorter range for echoes or propeller noises from a surface vessel.

Inversion layers of the type shown on Plate 6 have been found occasionally by the SEMMES during winter and early spring cruises. It seems probable that they might be more common during the summer but there are no data. Their effects have been discussed at some length because they illustrate so well the application of the principles developed in the previous discussion.

15. Range - Intensity Data

The SEMMES and S-20 have collected a large amount of data on the variation of the intensity of the direct signal transmitted from the SEMMES to the S-20 on the surface at different frequencies and under different water conditions. The series of curves, Plates 8 to 13, show the range-intensity curves and their associated temperature-depth curves for some broadly typical conditions. While these curves are

broadly typical, all gradations between them have been found at different times and places. The curves show the direct signal strength, but it was experimentally determined that for the equipment and technique used by the SEMMES and S-20, the echo intensity from the S-20 on the surface was 60 $\pm$ 5 db below the level of the direct signal. At speeds under 12 knots, 0 db was the threshold level for 17 kc echoes on the SEMMES, so that any time the direct signal received on the S-20 was 60 db or more, echoes from the S-20 on the surface could be heard on the SEMMES. The echo range may therefore be estimated roughly from these curves. The curves also show the loss coefficient, α, in decibels per thousand yards (kiloyards) for the different frequencies. The loss coefficient includes all the losses or gains the sound beam suffers from absorption, refraction, reflection, interference, scattering and perturbations of the axis of the beam due to pitching, rolling or accidental errors in setting. One outstanding point is that α is consistently less at the lower frequencies.

These data are presented to aid a destroyer screen without temperature measuring equipment or a submarine target in making an estimate of the possible echo range from a submerged submarine by means of an experimental range-intensity run between two surface ships at a particular time and place interpreted in the light of this discussion.

Plate 8 illustrates a somewhat better than average range-intensity run with its associated temperature-depth curve. It was taken beyond the 100 fathom curve on the Atlantic side north of Colon. The small positive temperature gradient at the surface and the two small inversions at 3 and 8 fathoms tend to refract the beam slightly upward and maintain a generally high intensity. The 60 db rule for 17 kc would give about a 4000 yard echo range between surface ships. One would expect good echo ranges from a submarine at any depth above 75 feet. Due to the considerable negative gradient beginning at 13 fathoms, ranges would diminish on a target at greater depths.

Plate 9 was taken in the same area as Plate 8 and is given to show the large fluctuations in intensity that may result from a temperature gradient curve as shown. The negative gradient down to 7 fathoms refracts the beam downward, but the positive gradient from 12 to 14 fathoms refracts it upward; and, since there are many paths of slightly different lengths, there will be strong reinforcements and interferences producing the fluctuations in intensity, although the average values for α are the same as for Plate 8.

Plate 10 is rather typical of conditions beyond the 1000 fathom curve on the Pacific side off Panama Bay. The loss coefficient, α, is extremely high for the first 2000 yards and then becomes extremely low. The initially steep slope follows from the large negative temperature

gradient near the 5 fathom depth, (note that the temperature scale is five times that of previous curves) but there are no adequate experimental data to explain $\alpha = 0.7$ db/Kyd from 2000 to 15,000 yards. Provisionally, one may assume a considerably higher salinity in the cold water that slowly refracts the beam upward, or the effect may be due to reflections from the turbulent layer between the hot and cold water.

Plates 11, 12, and 13 show an interesting daily cycle that is frequently found in calm weather off Guantanamo in January to March and illustrates the application of the preceding explanations to an analysis of experimental data. Plate 11 shows a range intensity run from 0837 to 0932 after a night of rather strong winds averaging 16 knots and reaching a maximum of 28 knots. The upper hundred feet of water is therefore thoroughly mixed and the temperature gradient is $-0.0006\,^{\circ}$C per meter. Although this is a negative temperature gradient, Plate 2 shows that the beam would be bent upward due to the pressure gradient. The signal is therefore maintained at a high level throughout the run and $\alpha = 2.36$ db/Kyd at 17.6 Kcs.

Plate 12 taken from 1225 to 1324 on the same day shows an entirely different picture for both range-intensity and temperature-depth curves. The wind had dropped to 3 knots by 1130 and was 1.5 knots by 1300, so the sea was dead calm while the sky was bright and clear all morning. This resulted in building up a gradient of $-0.3\,^{\circ}$C/M for the first 12 feet of $-0.017\,^{\circ}$C/M for the next 12 feet and $-0.0024\,^{\circ}$ C/M down to 100 feet. The first two layers would bend the beam sharply downward, and the layer below 25 feet would bend it upward, but the pressure gradient alone would not bring it back to a peak value at 4500 yards. No data are available on the temperatures below 100 feet or on the salinity gradient. It seems logical to assume a positive salinity gradient to aid the pressure gradient in bending the beam upward. Range-intensity curves of this type show the so-called "afternoon effect" and the "skip distance" effect. Echoes cut off sharply at 1000 yards or less, but may come in again around 4000 yards.

Between 1500 and 1700, a 13 to 16 knot wind came up which mixed the upper layers of water, and after the sun went down radiation and evaporation cooled the surface layer so that by 2000 to 2200, we had the condition shown on Plate 13 with a high level of intensity and $\alpha = 2.4$ db/Kyd.

The experimental data given in Plates 8 to 13 certainly emphasize the point that too general conclusions about water conditions in a given area must not be drawn from a simplified theory or limited data. Thus, if one measured the intensity of the direct signal at 17.6 kcs. on Plate 12 between 2000 and 4000 yards only, he would find a gain in intensity of 15 db/Kyd instead of a loss as the range increased.

Similarly, tests made at 0900, Plate 11, or 2100, Plate 13, would rate Guantanamo as excellent for echo-ranging, but if made at 1300, Plate 12, the rating would be very poor at 1000 to 3000 yards, but might be good at 4500 yards.

16. Conclusions

From the above discussions, one might be tempted to conclude that sound equipment had little chance to be effective or reliable. Fortunately, many of the limitations are abnormal rather than normal, and there are many more times and places where conditions are fair to good than where they are very poor, just as in most places there are more clear days than foggy ones. The analogy between water conditions for sound transmission and atmospheric conditions for light transmission is rather close. One does not expect to see much in fog or darkness and accepts that limitation or takes advantage of it, so one should not expect to get echoes through a temperature inversion, but a submarine may use it as a means of escape.

Present plans provide for a more extensive study of water conditions, particularly the oceanographic features, in important operating areas and their correlation with sound propagation. The new data will be incorporated in future reports as soon as available.

BIBLIOGRAPHY

1. Velocity of Sound in Sea Water, Stephenson, Physical Review, Vol. 21, p. 181-185, February, 1923.

2. Velocity of Sound in Sea Water, Heck and Service, USC and GS, Special Publication No. 108, 1924.

3. Tables of the Velocity of Sound in Pure Water and Sea Water for Use in Echo-Sounding and Sound-Ranging, Hydrographic Dept., British Admiralty, 1927 and 1939.

4. Velocity of Sound in Sea Water and Calculations of the Velocity for Use in Sonic Sounding, Kuwahara, Hydrographic Review, Vol. XVI, No. 2, November, 1939, pp. 123-140.

5. Absorption Coefficients, Naval Research Laboratory Report S-1204, October, 1935.

6. Sound Analysis of the S-20, Naval Research Laboratory Report S-1282, June, 1936.

7. Underwater Sound Investigations in Northern Waters, August, 1937, Bureau of Ships file S68(1-28-W6).

8. Investigation of Turbulence beneath a Destroyer, Naval Research Laboratory Report S-1413, December, 1937.

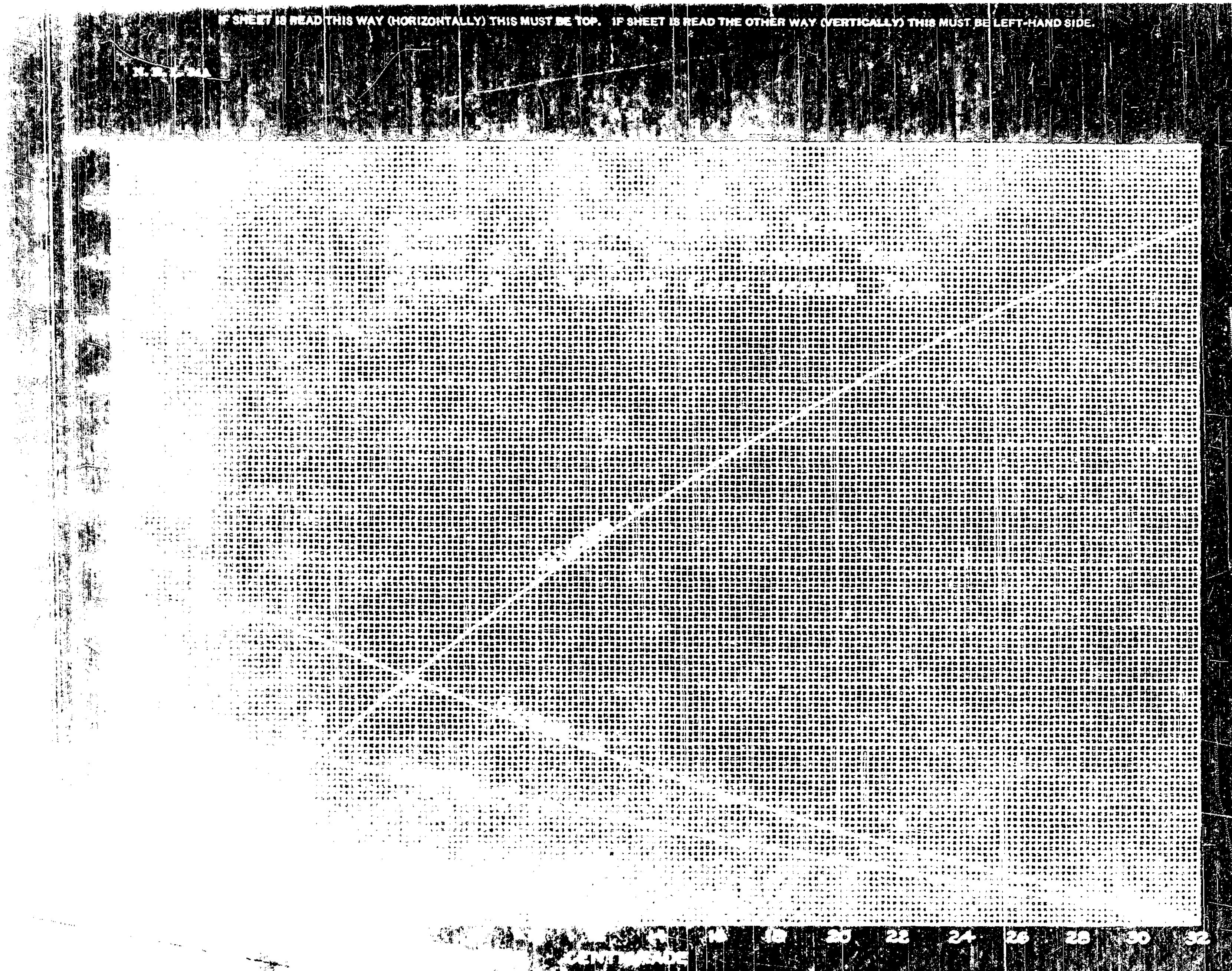
9. Absorption Coefficients, Naval Research Laboratory Report S-1466, August, 1938.

10. Surface Motion of Water Induced by Wind, Science, Vol. 87, No. 2250, February 11, 1938.

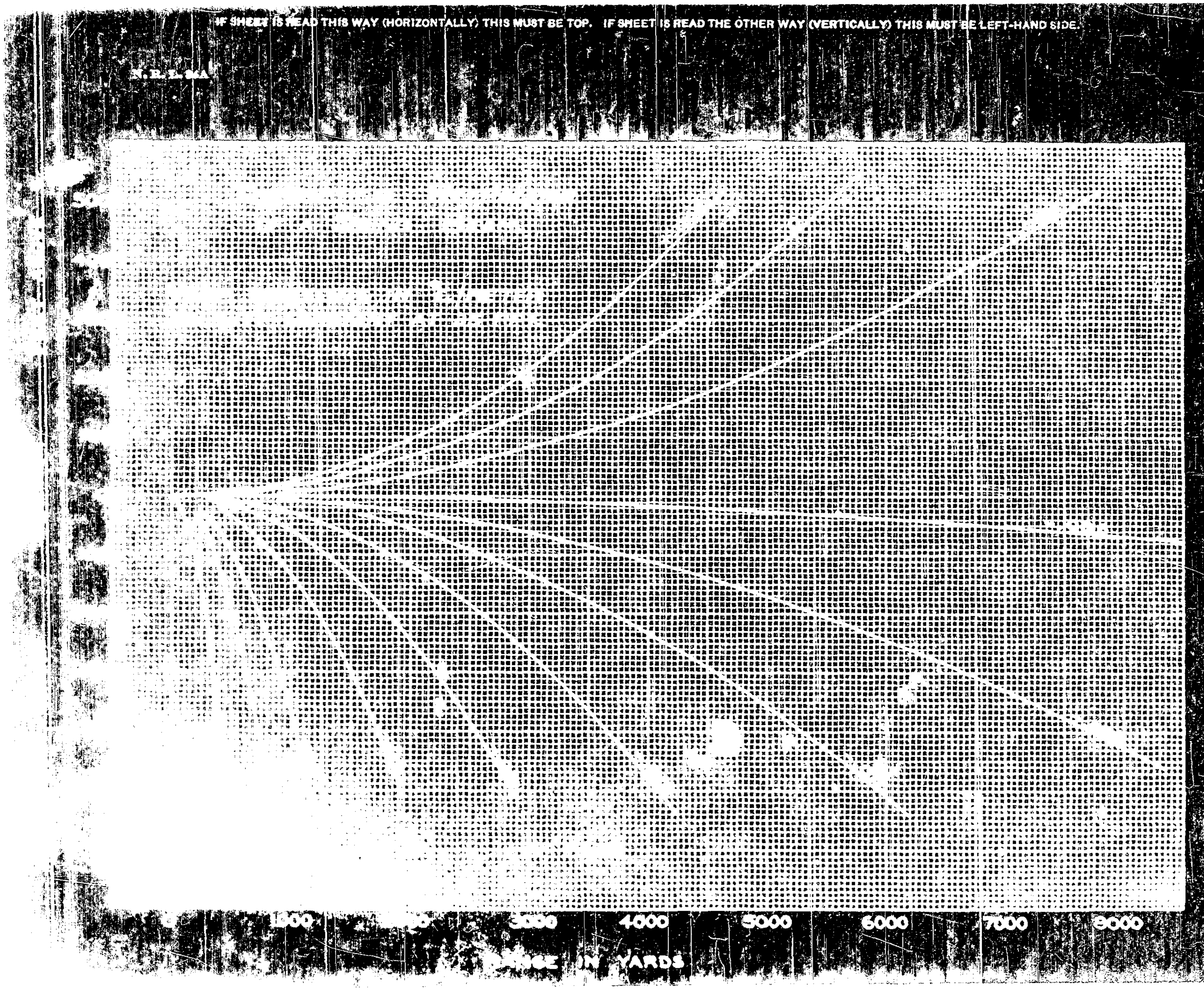
11. Absorption Coefficients of Supersonic Sounds in Open Sea Water, Naval Research Laboratory Report S-1549, August, 1939.

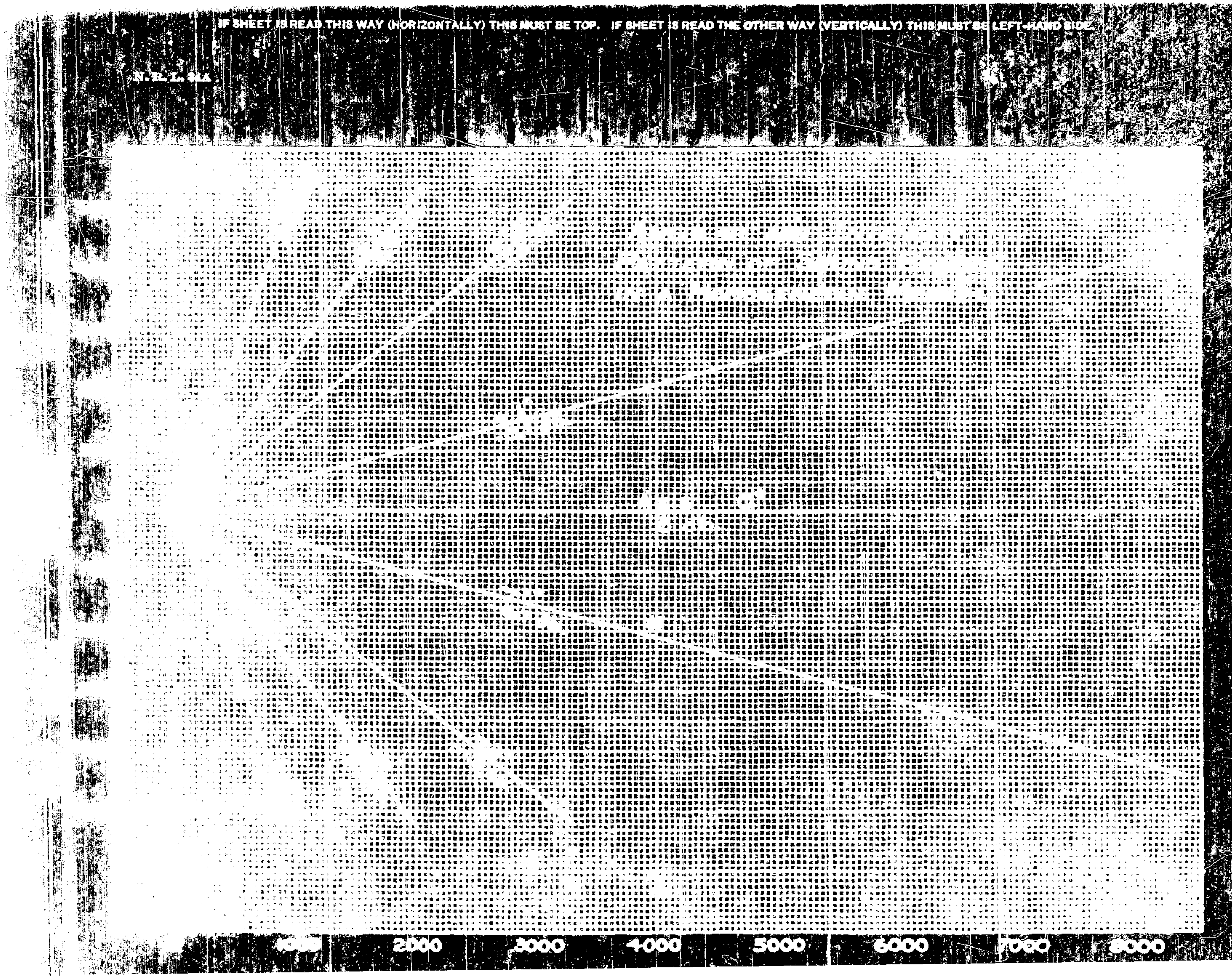
12. Deep Dive Echo-Ranging and Propeller Noise Tests with the R-4, Naval Research Laboratory letter to Bureau of Ships, October, 1939.

13. Velocity and Ray Paths of Sound Waves in Deep Sea Water, by Swainson, USC and GS Report, April, 1934.



IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.
18
20
22
24
26
28
30
32

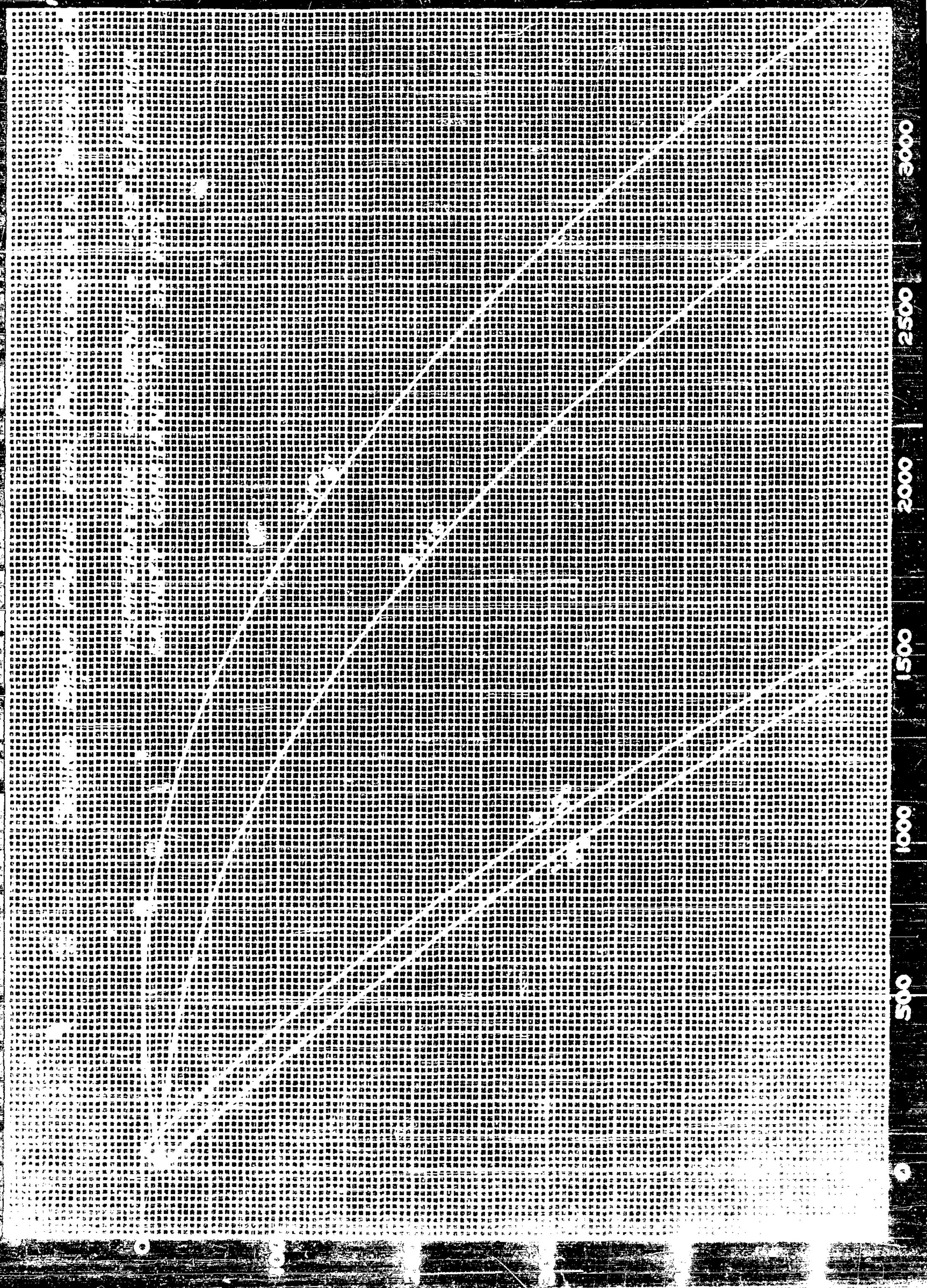

IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.
N. R. L. 84A
1000
3000
4000
5000
6000
7000
8000
YARDS


IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.
N. R. L. 84A
2000
3000
4000
5000
6000
7000
8000

U. S. NAVAL RESEARCH LABORATORY
BELLEVUE, D. C.

DATE

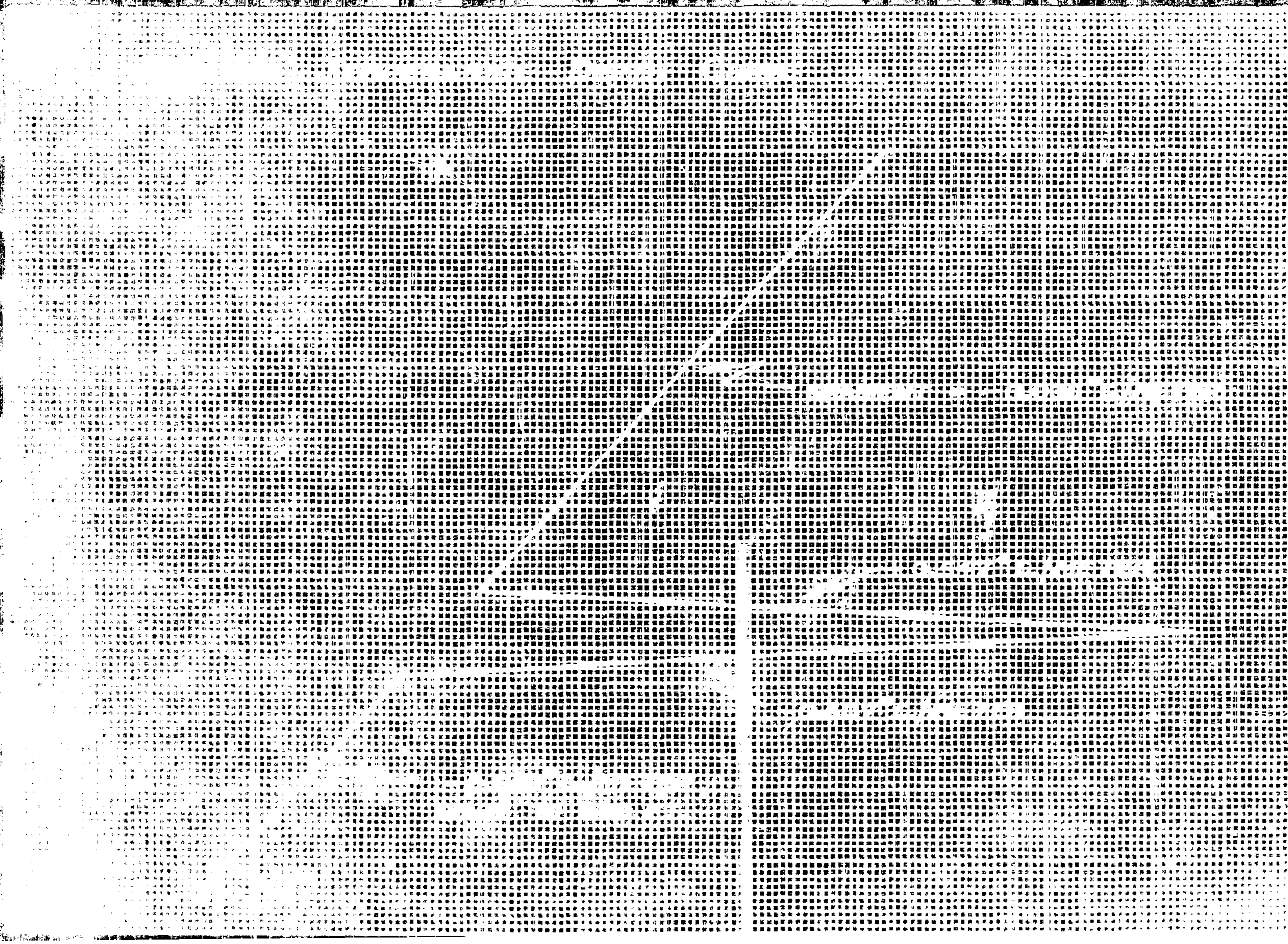
IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.

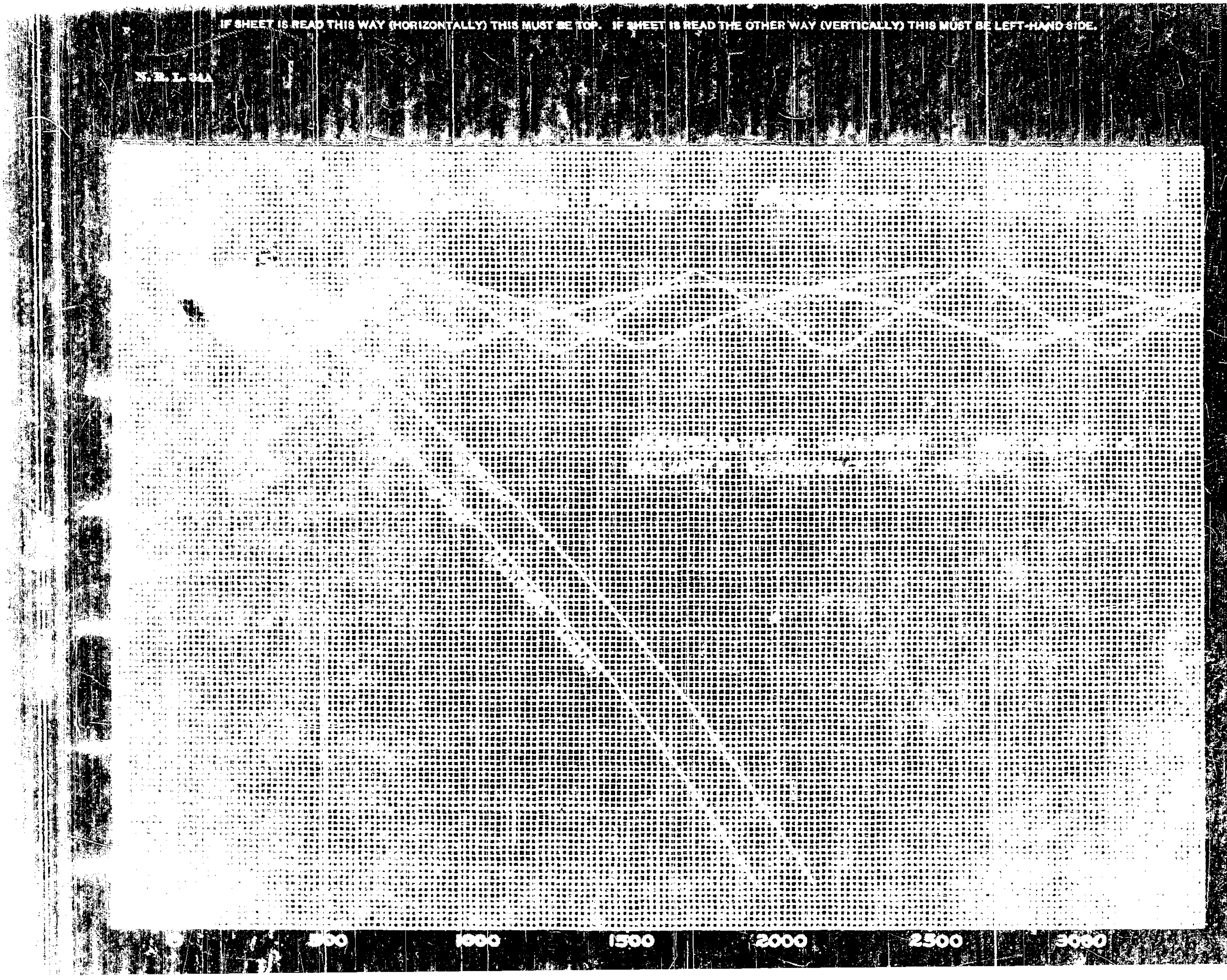


N. R. L. 3A

IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.

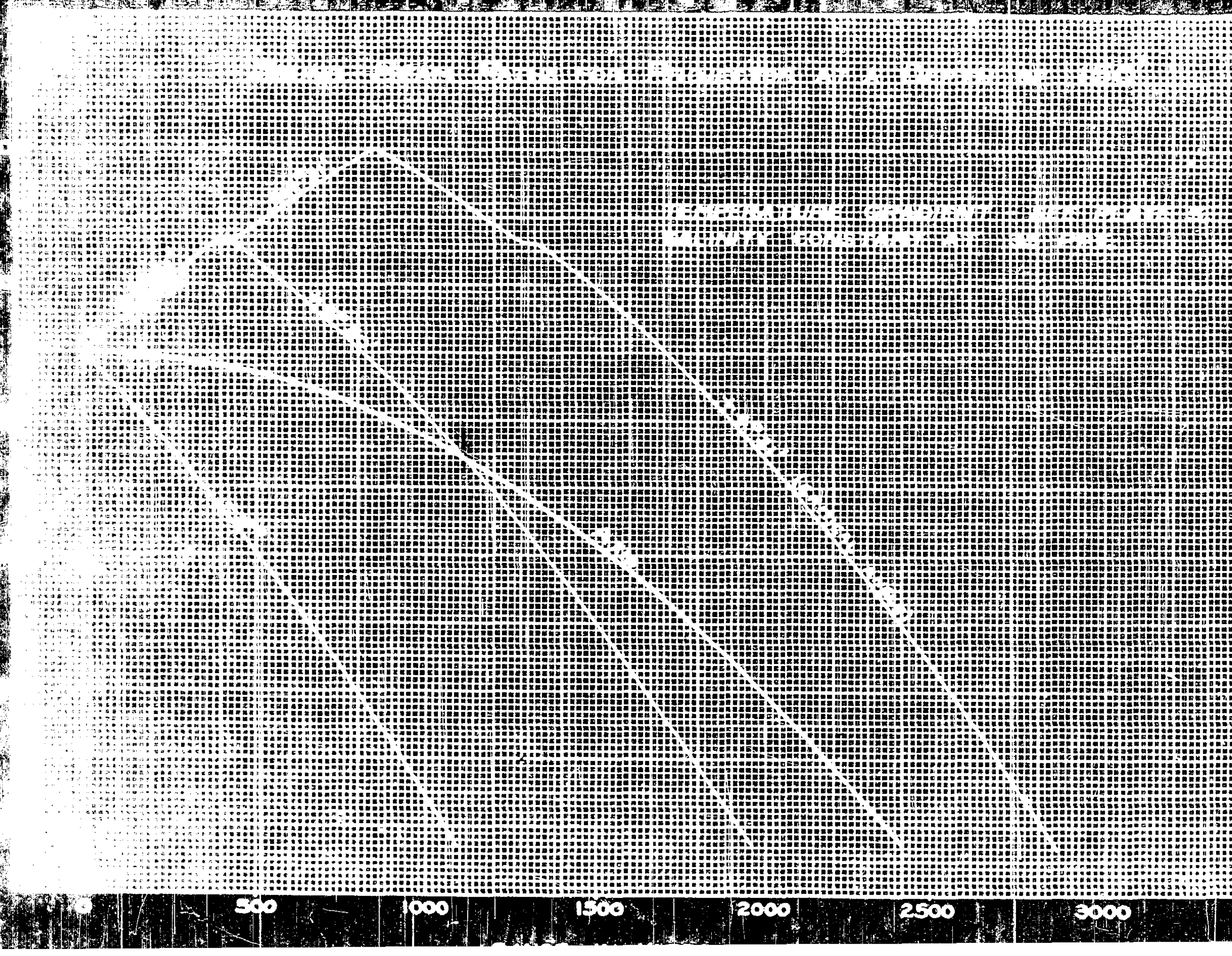
N. R. L. 34A

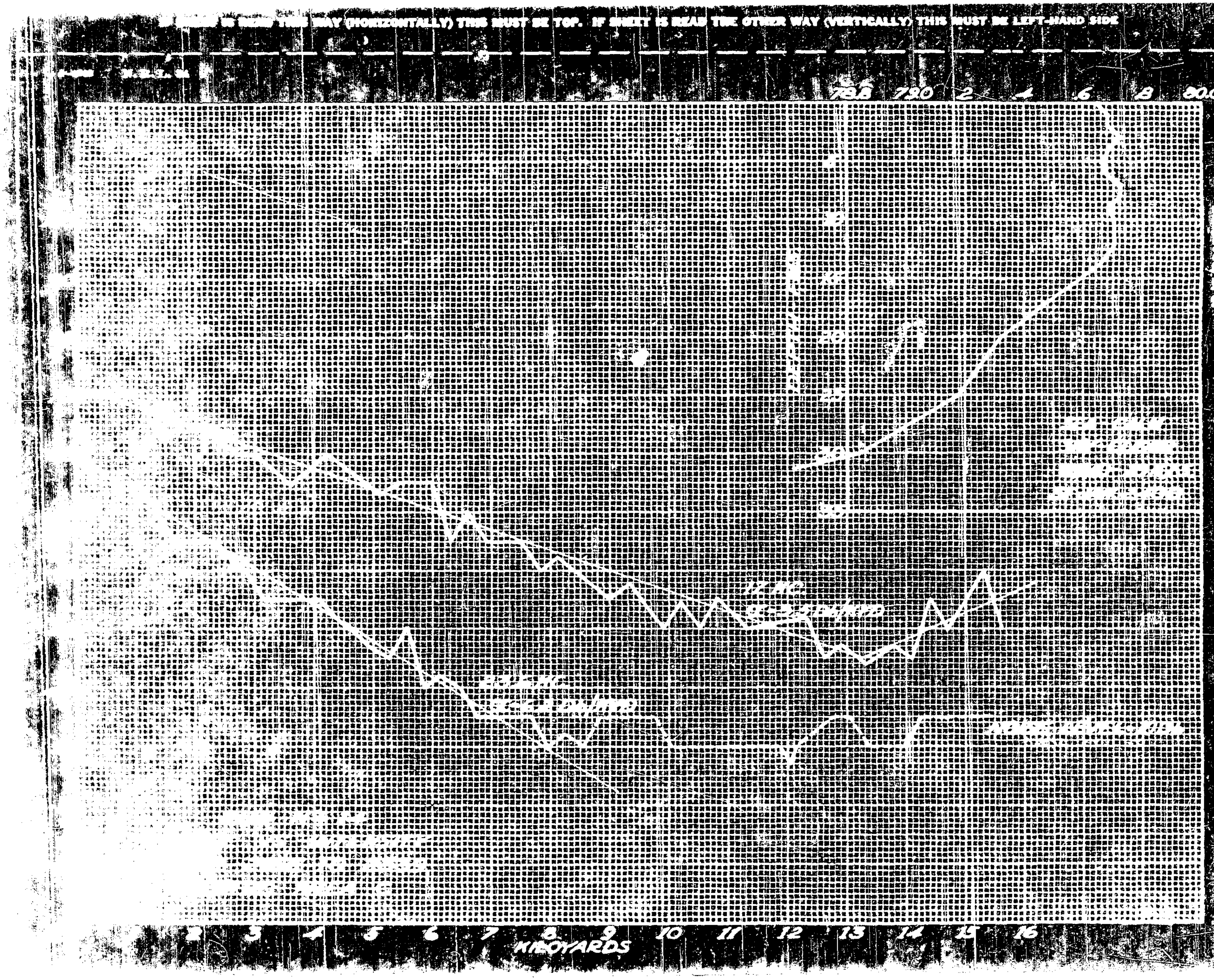



IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.
N. R. L. 34A
500
1000
1500
2000
2500
3000

IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.

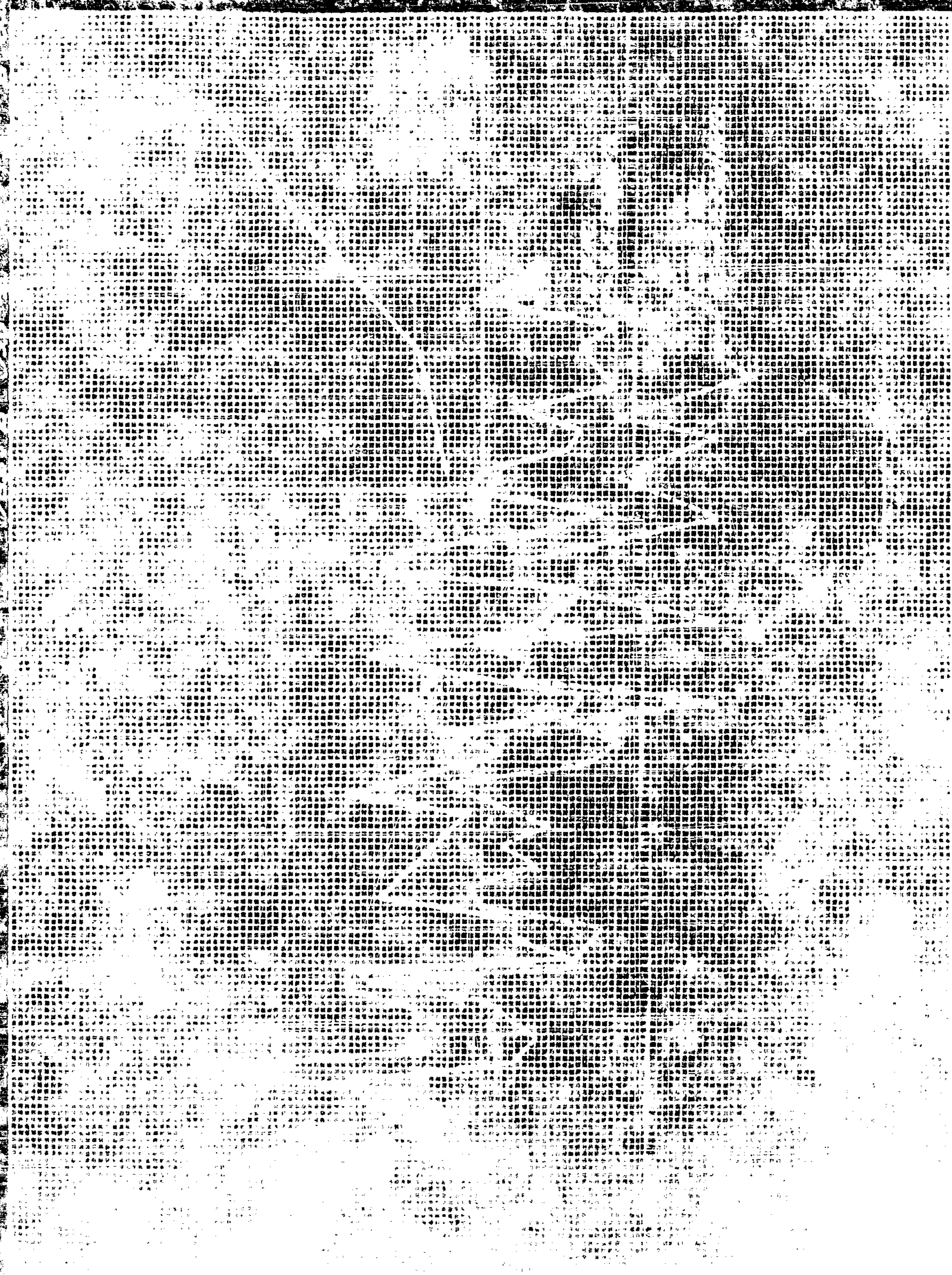
N. R. L. 34A

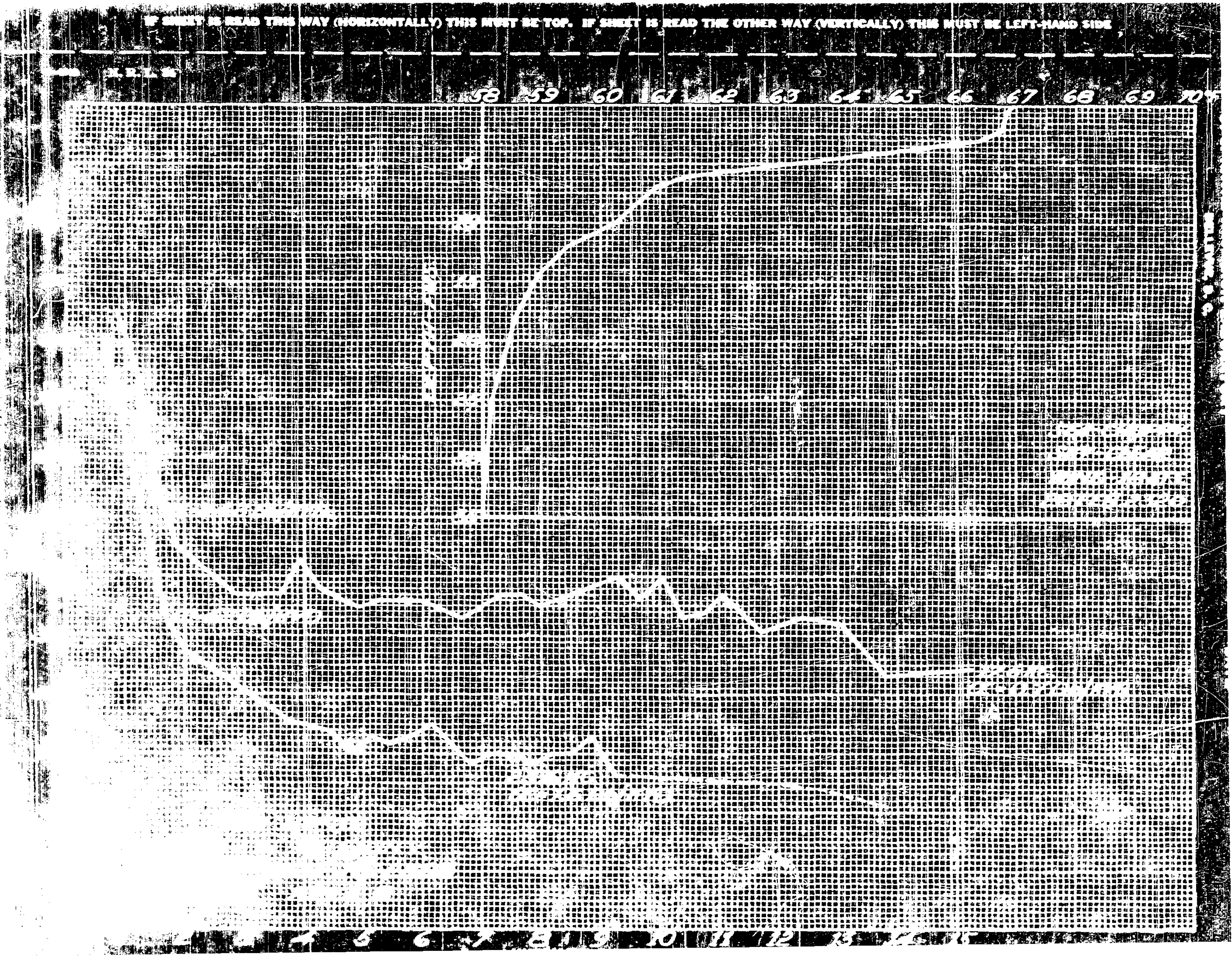




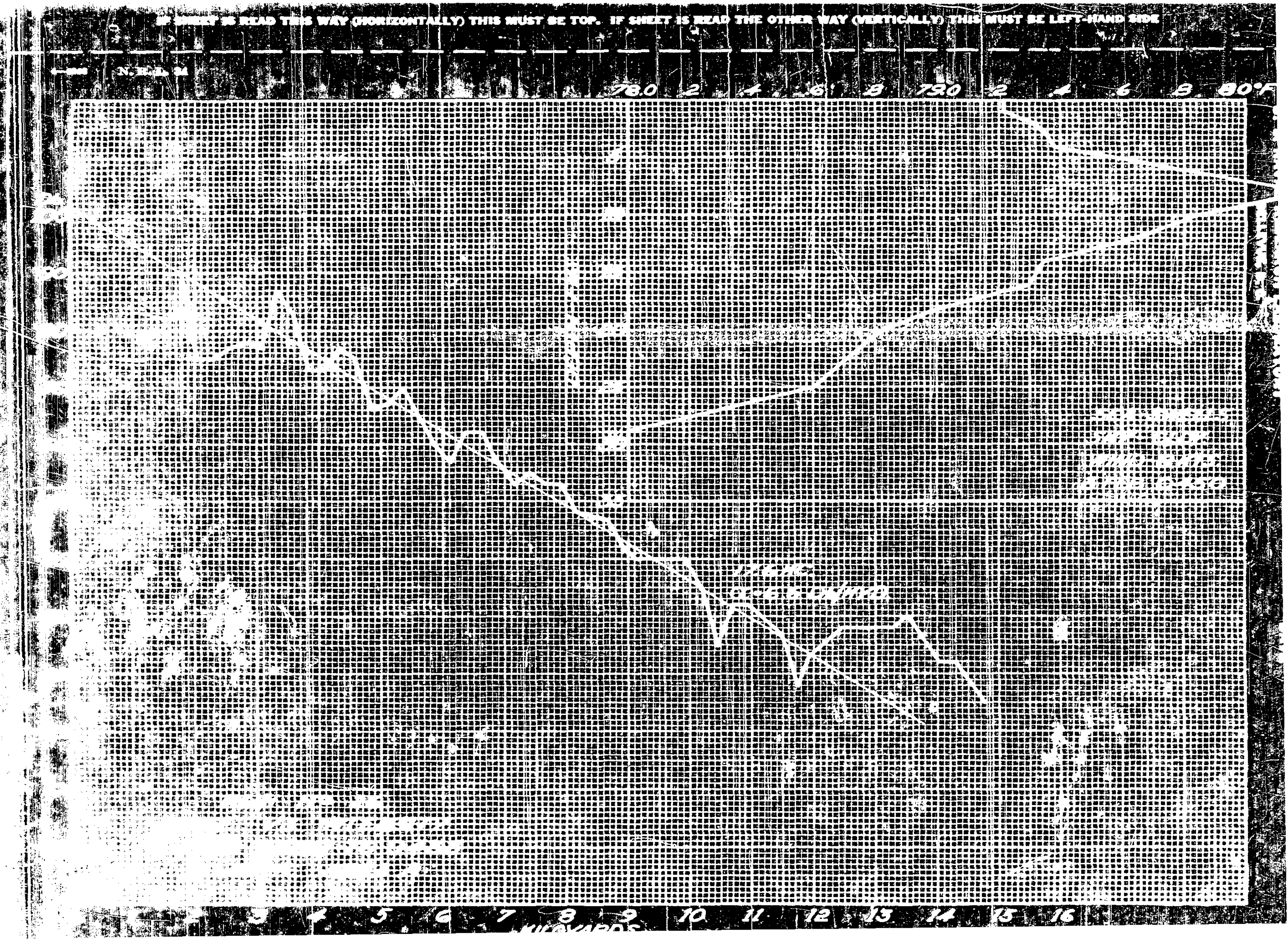
IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE
BELLEVUE, D. C.
78.8 79.0 2 4 6 8 80.0
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
KILOYARDS

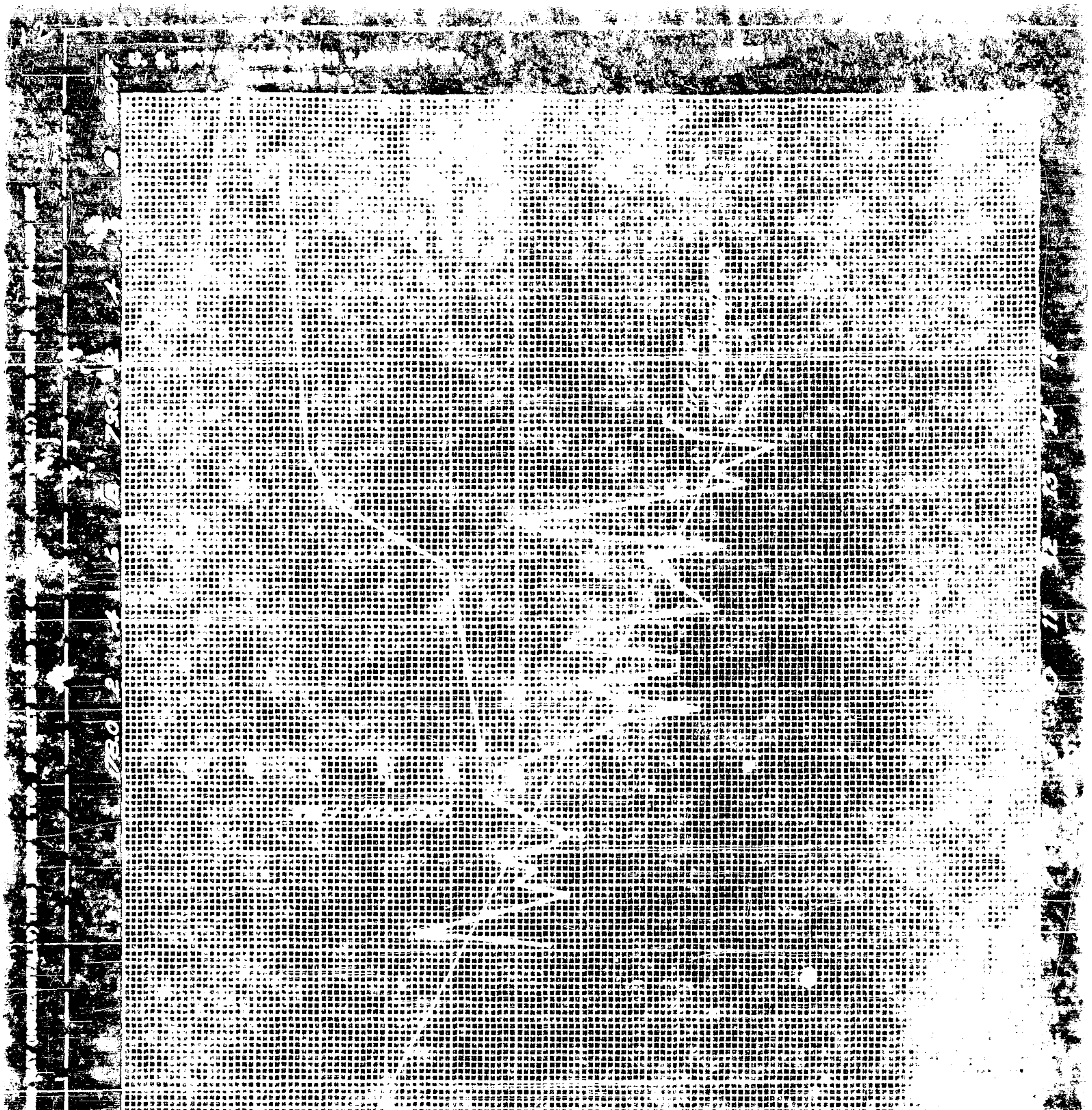
DATE

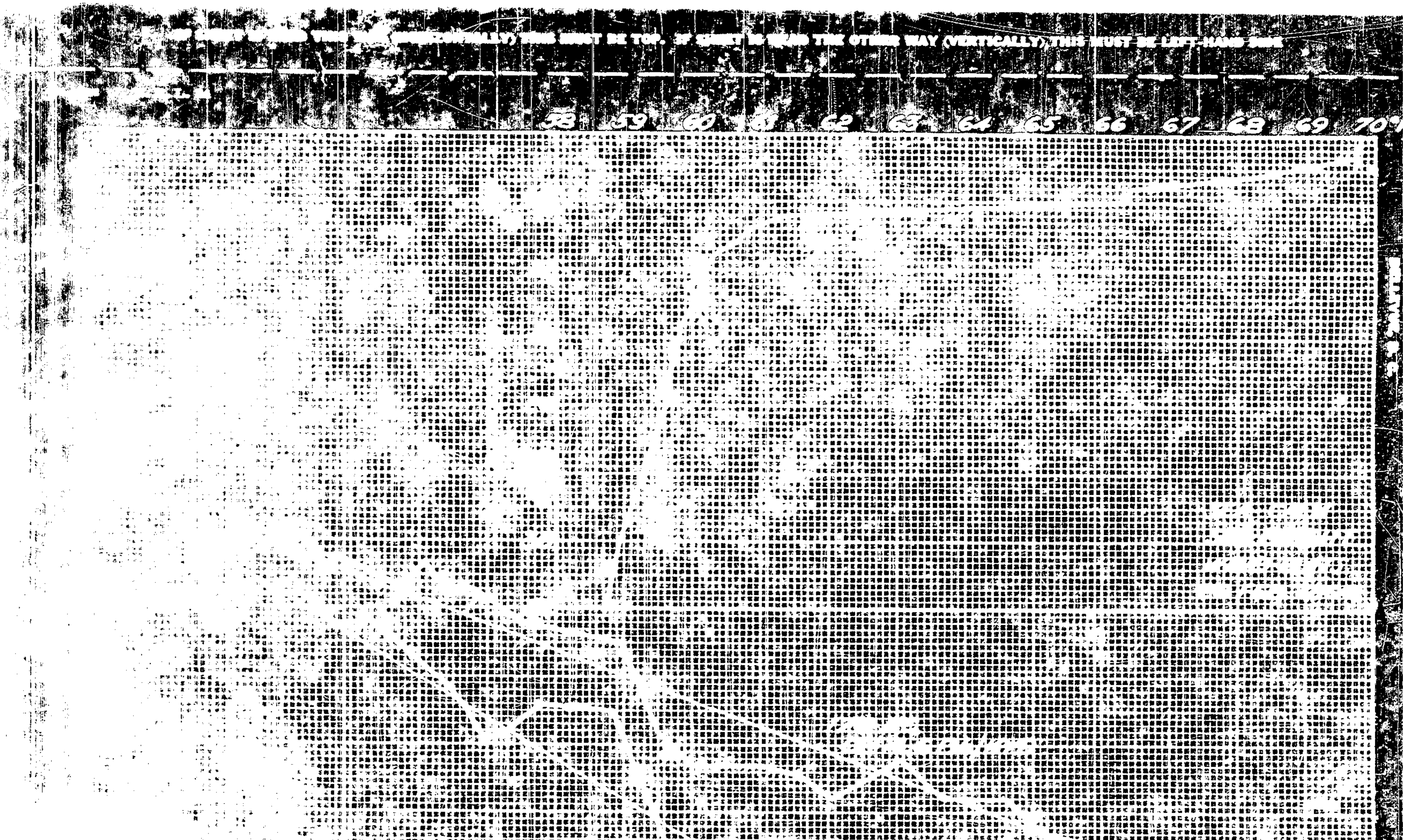




IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE
BELLEVUE, D. C.
58 59 60 61 62 63 64 65 66 67 68 69 70
6 7 8 9 10 11 12


IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE
78.0 2 4 6 8 79.0 2 4 6 8 80°F
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
KILOYARDS




THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE
58 59 60 62 63 64 65 66 67 68 69

UNITED STATES GOVERNMENT

memorandum

7103/911

DATE: 25 August 1999

FROM: Burton G. Hurdle (Code 7103)

SUBJECT: REVIEW OF REFS. (a) THROUGH (c) FOR REMOVAL OF RESTRICTIONS

TO: Code 1221.1 8/27/99

VIA: Code 7100

REF: (a) NRL Report S-1204, 16 Oct 1935, E.B. Stephenson AD-491 574
(b) NRL Report S-1670, 3 Dec 1940, E.B. Stephenson AD-135 780
(c) NRL Report S-1722, 11 April 1941, E.B. Stephenson and F.J. Woodsmall AD 221 613

1. References (a) through (c) are a series of reports and documents in underwater acoustics. Refs. (a-c) have been declassified earlier, but restrictions still exist.

2. The science, technology, equipment and operational utility of these reports have long been superseded. The current value of these reports is historical.

3. Based on the above, it is recommended that references (a) through (c) be available with no restrictions.

Burton G. Hurdle
BURTON G. HURDLE
Acoustics Division

CONCUR:

Edward R. Franchi 8/26/99
EDWARD R. FRANCHI Date
Superintendent
Acoustics Division

OPTIONAL FORM NO. 19
(REV). 1-80)
GSA FPMR(41 CFR) 101-11.6
5010-114